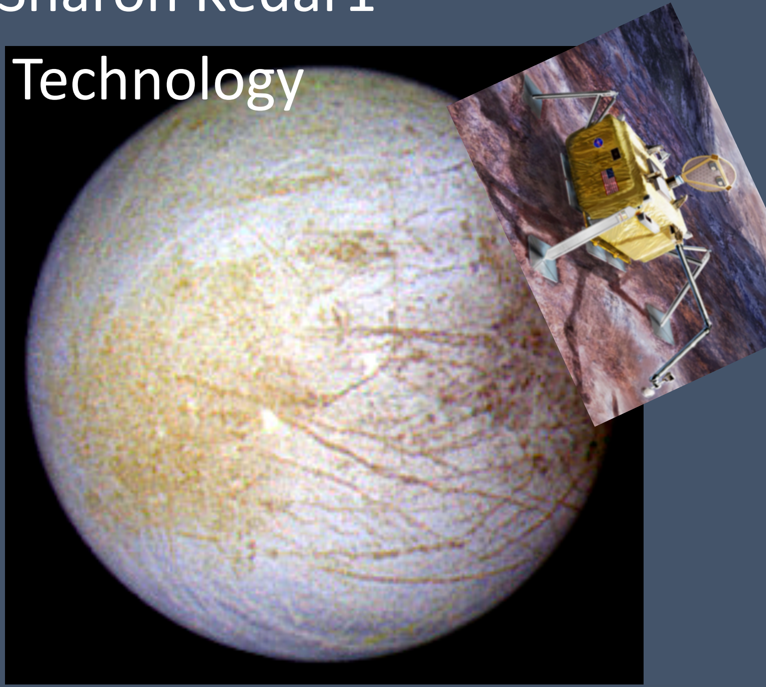
Planetary seismology reborn: Prospects for exploring interiors on Mars, icy ocean worlds and beyond

Mark Panning[1], Simon Stähler[2], Steven D. Vance[1], and Sharon Kedar1

1. Jet Propulsion Laboratory, California Institute of Technology
2. ETH Zürich

EPSC, 20 September, 2018

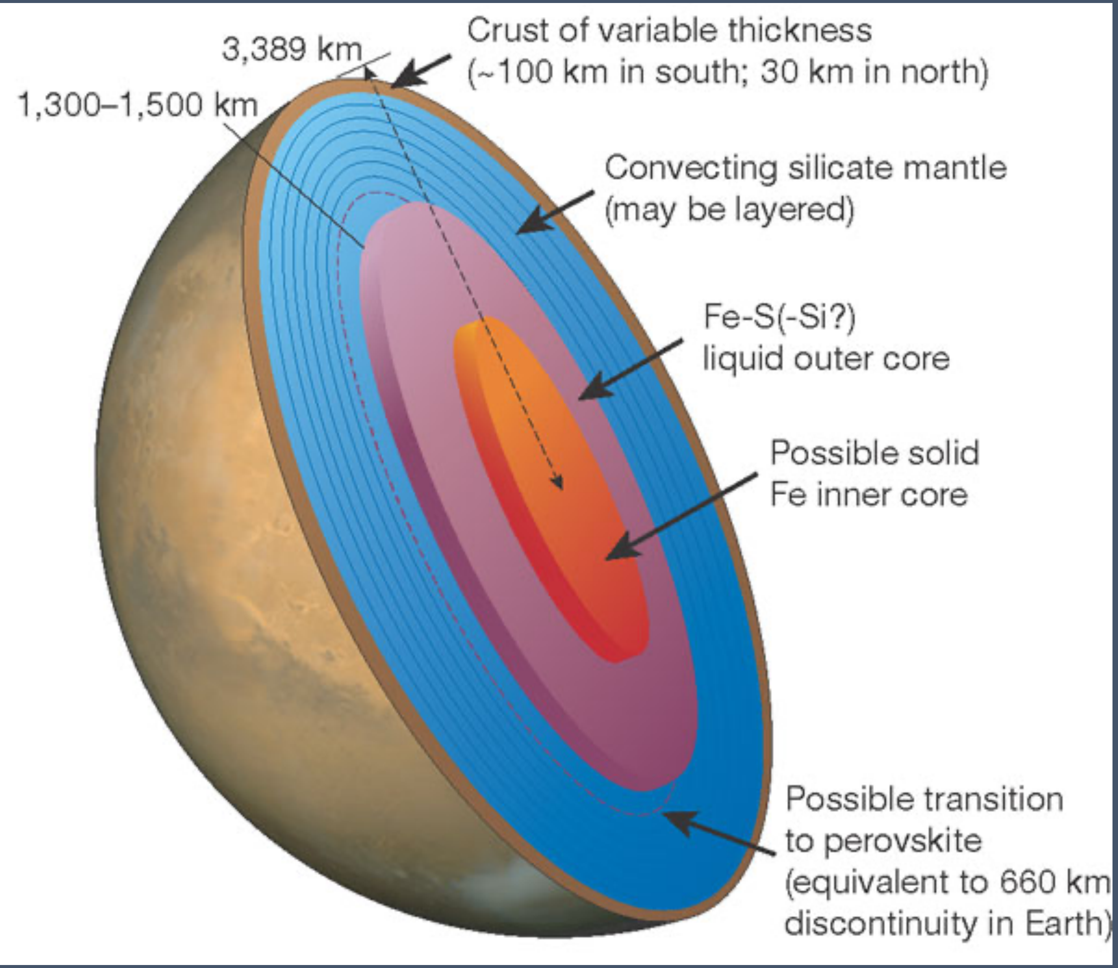


Jet Propulsion Laboratory
California Institute of Technology

ETH zürich

Why planetary seismology?

- Most of our detailed knowledge of the interior structure of the Earth comes from seismology
- Most of what we know about planetary interiors comes from gravity and topography measurements plus educated guesses about chemistry
- Trying to figure more about the evolution of Europa, Titan, Mars, or any other planetary body requires the extra detail that seismology gives us

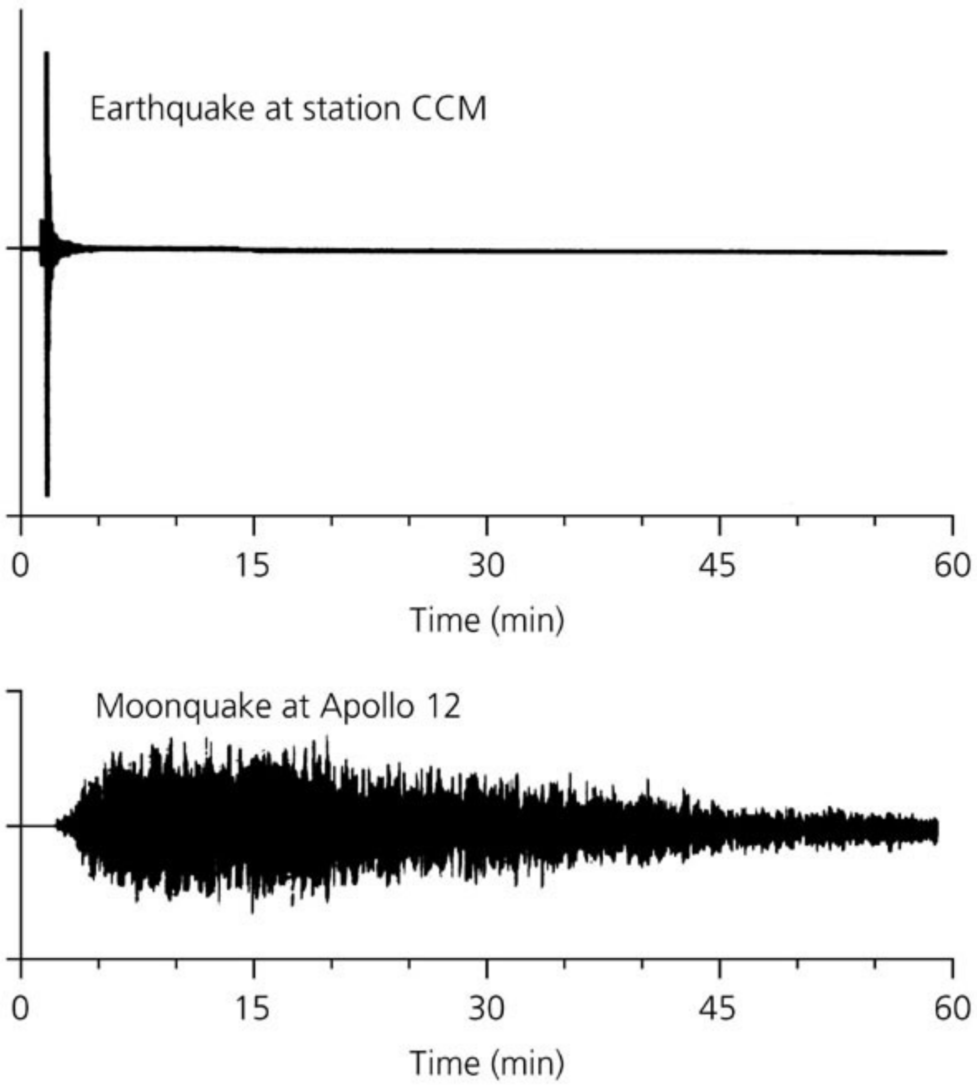


Core radius on Mars currently has 100's of kms of uncertainty and there is no constraint on an inner core. Figure from Stevenson, 2001

History of planetary seismology

- The “good”: Seismometers were placed on Earth’s moon and recorded data (Apollo 11, 12, 14, 15, and 16 missions plus active source on Apollo 17 - 1969-1972)
- Data recorded until 1977 (last data came in when I was 2 months old)
- Other data of note:
  - 2 Venus Venera landers included geophones that counted how often amplitude exceeded some threshold
  - The Philae lander from the Rosetta mission also included high-frequency geophones

Figure 3.7-10: Comparison of seismograms on the earth and moon.



History of planetary seismology

- The "bad": Viking landers included seismometers
  - 1 didn't "uncage" – no data
  - The other primarily only recorded the rocking of the lander due to wind.

Mars 96 never reached Mars due to launch stage failure

Viking landers had instruments on the lander deck (We'll revisit this at the end)

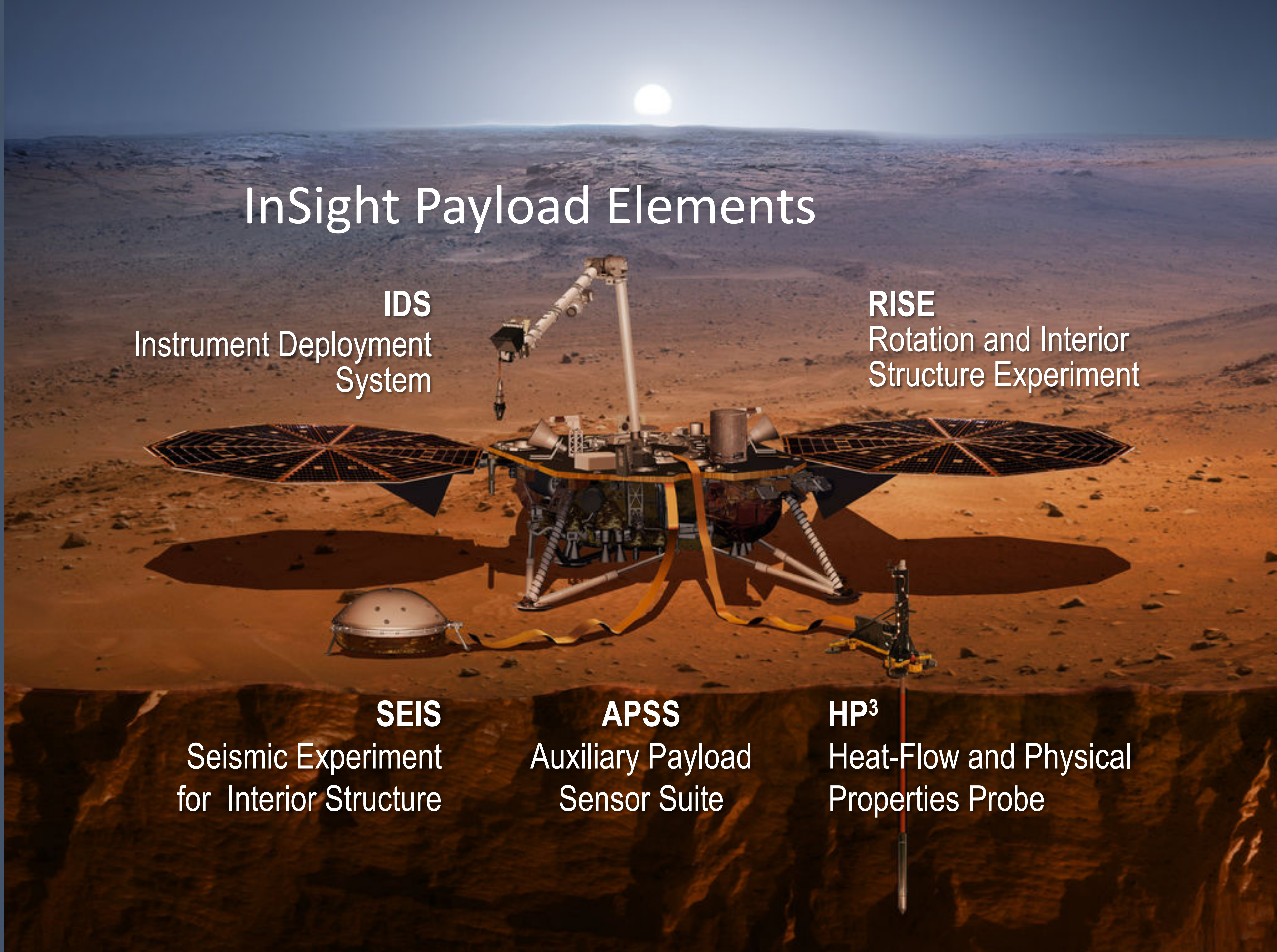
- The "ugly": At least 10 other seismometers have been included in launched missions that failed for a variety of reasons

InSight

Launched successfully on May 5

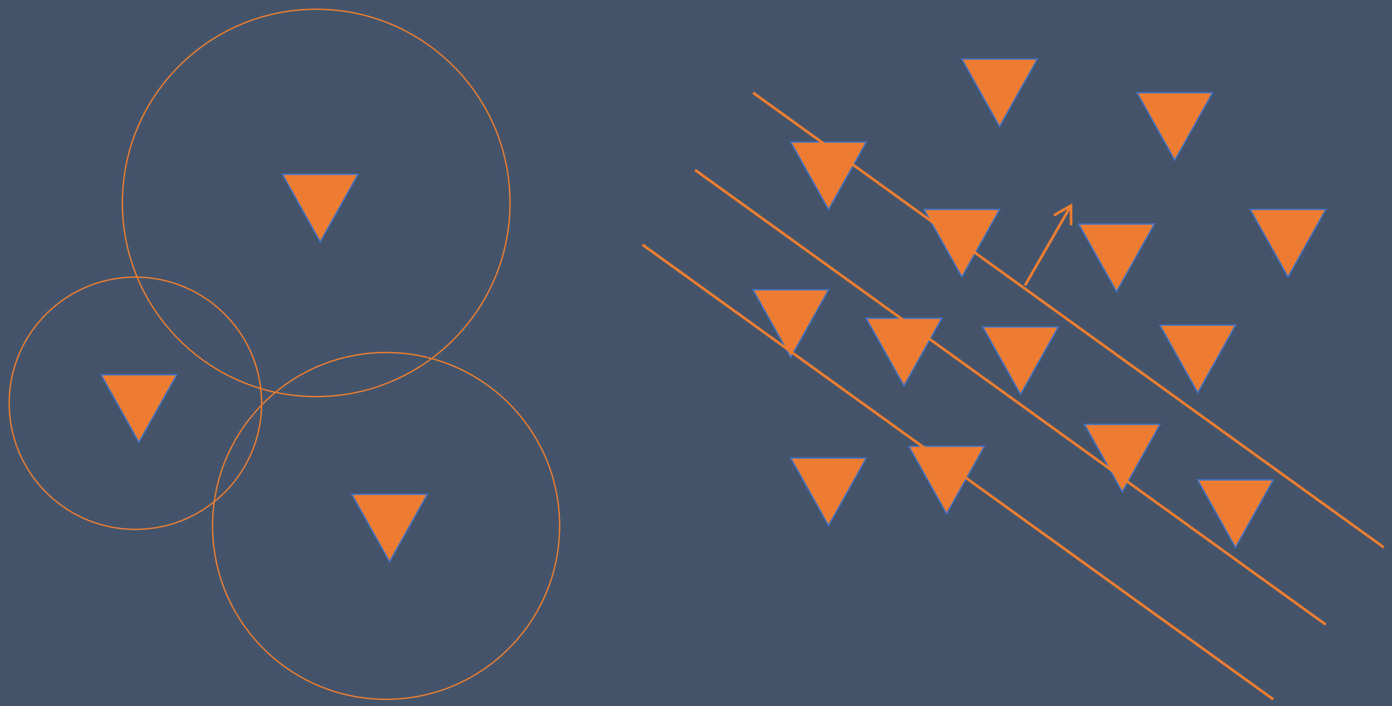
Landing on November 26

Primary mission extends for 1 martian year (2 Earth years)



Seismic networks vs. single station

- Modern seismology relies on networks
  - Accurate locations and origin times
  - Array seismology techniques

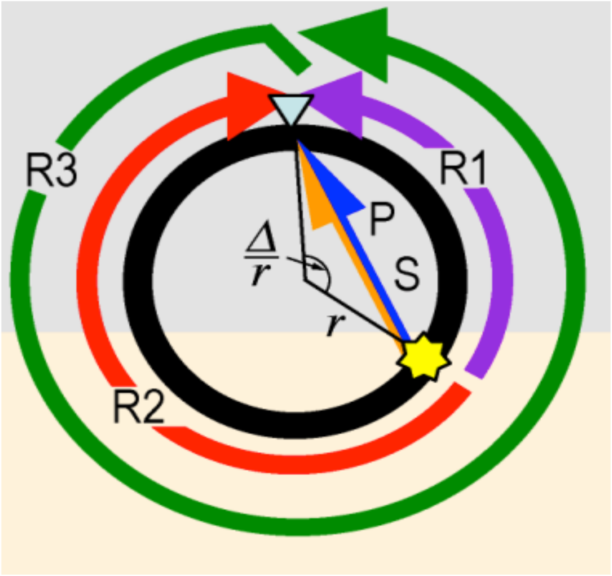


- Having a network on Mars would be wonderful (and it's been proposed many times)
- Having one station allows for an infinite relative increase in our seismic data, though!
- Two options for how to proceed if we want to model the interior seismic structure of Mars
  - Techniques that don't require location information
  - Single station location techniques

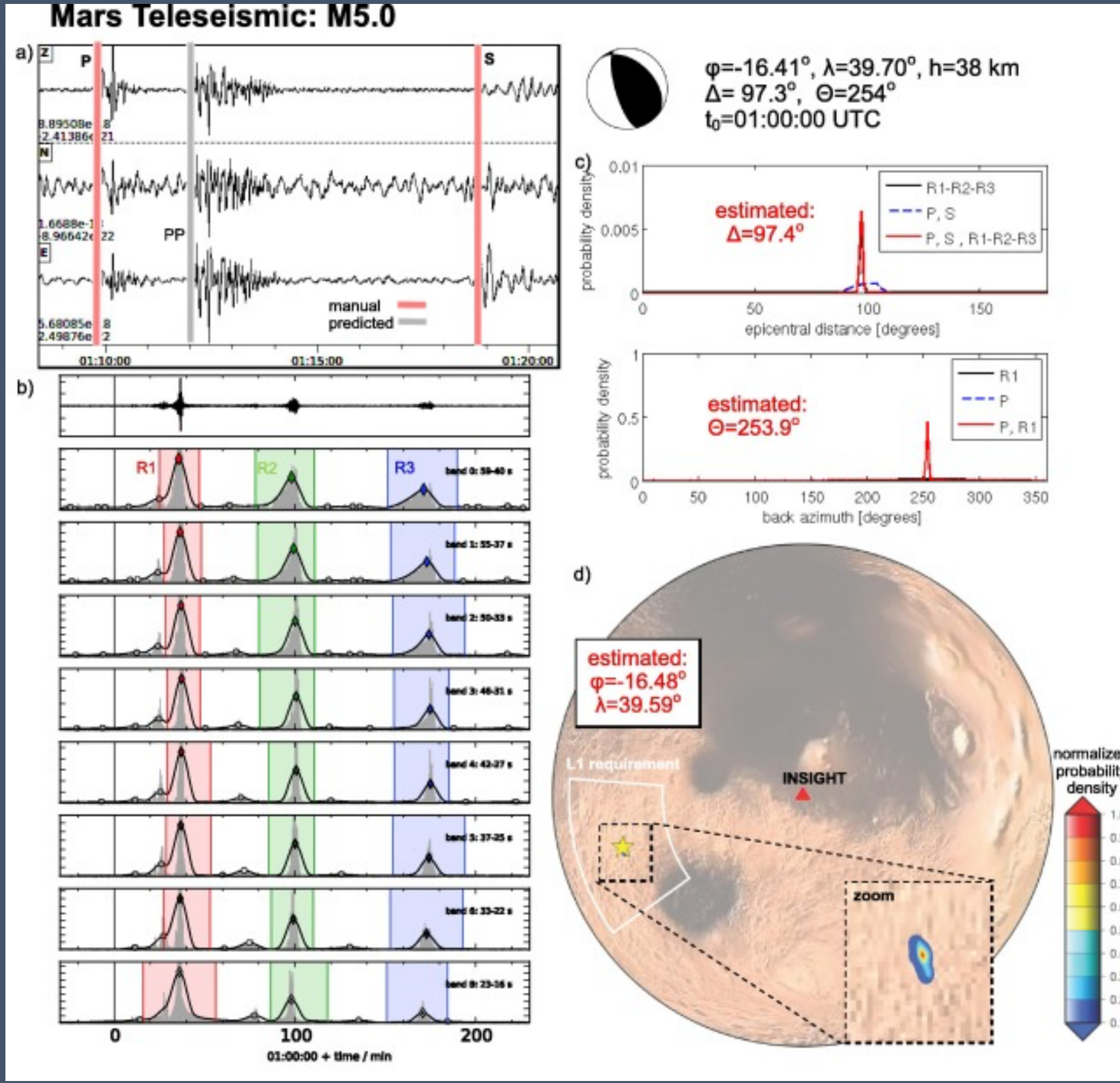
Single station location

- We estimate location using the timing of 3 orbits of surface waves (called R1, R2, and R3). There are 3 unknowns: Δ, the distance, t_0, the origin time, and U, the surface wave group velocity.
  - $U=2\pi/(R3-R1)$
  - $\Delta=\pi-U(R2-R1)/2$
  - $t0=R1-\Delta/U$

Smaller events require structural models when looking at P and S arrivals

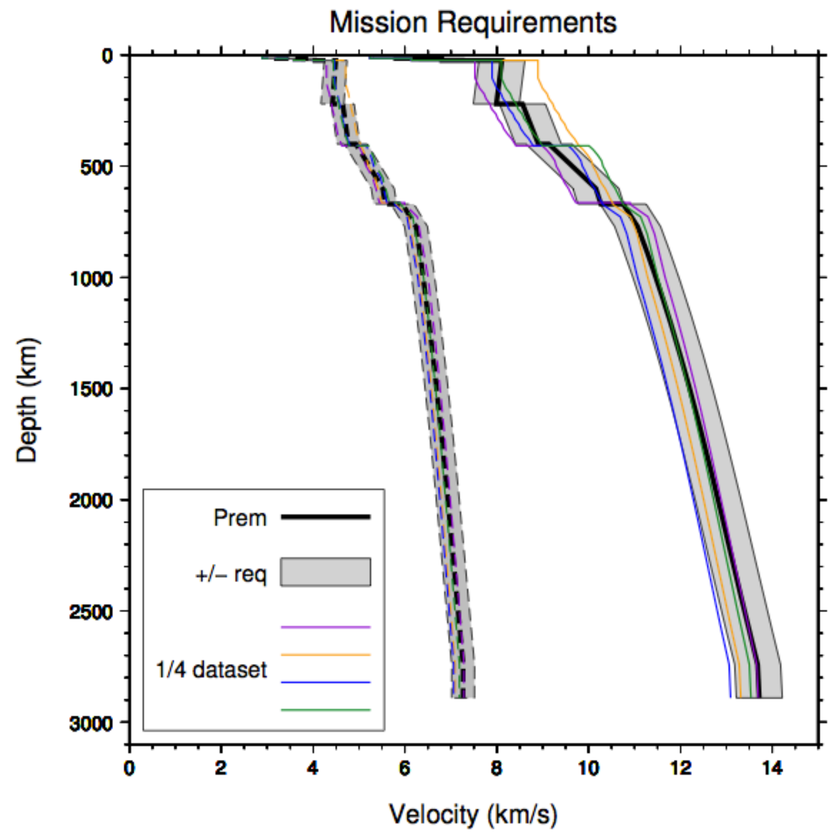


Cartoon from J. Clinton, ETH

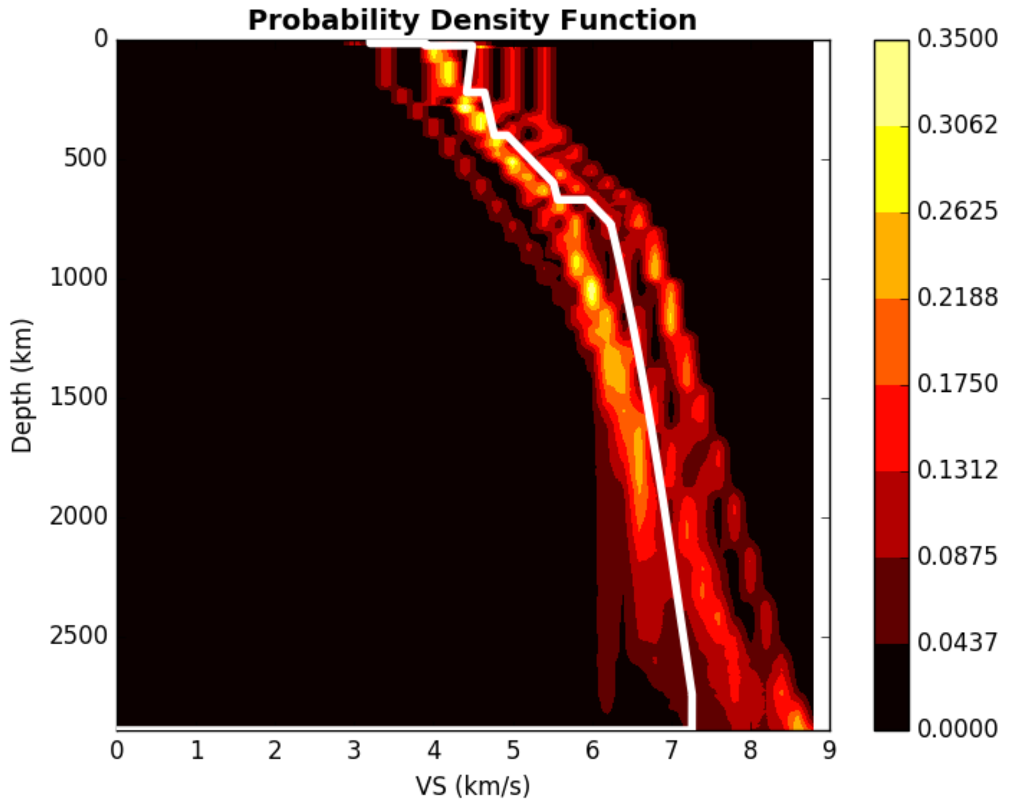


From Böse et al., 2016

Testing with Earth data from a single station



With subsets of 7 “big” events using Panning et al., 2015



With only 5 smaller events using Bayesian inversion for source and structure (Panning et al., 2017)

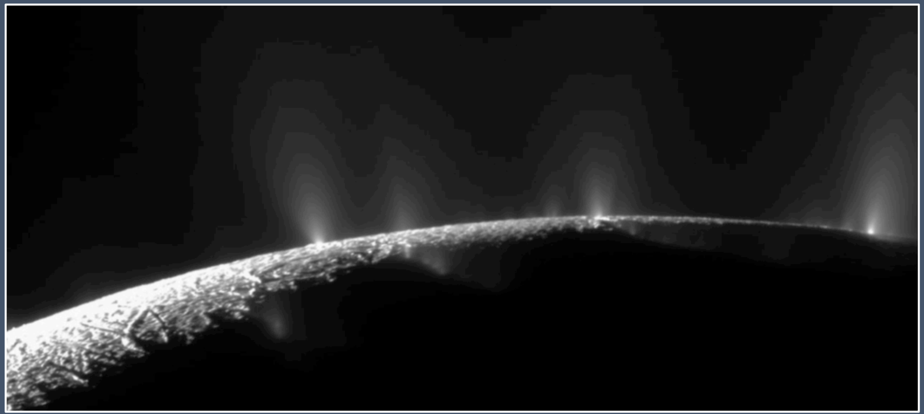
Seismology on Europa, Titan and ocean worlds

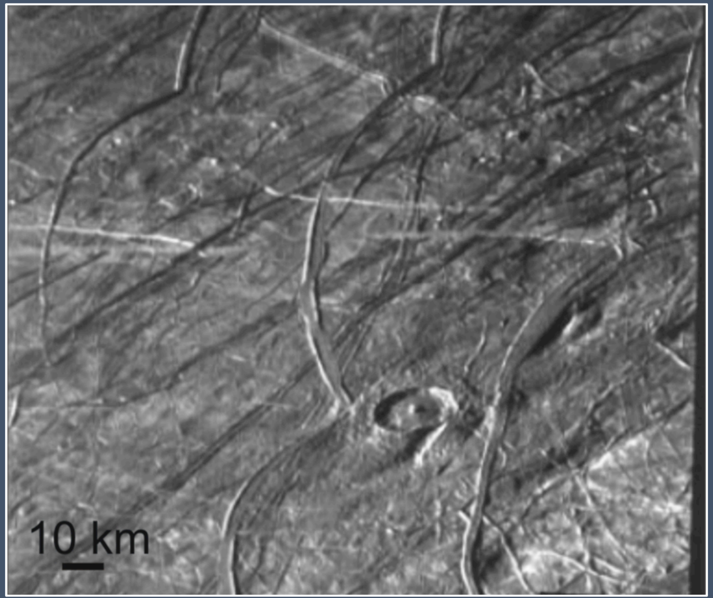
Sources

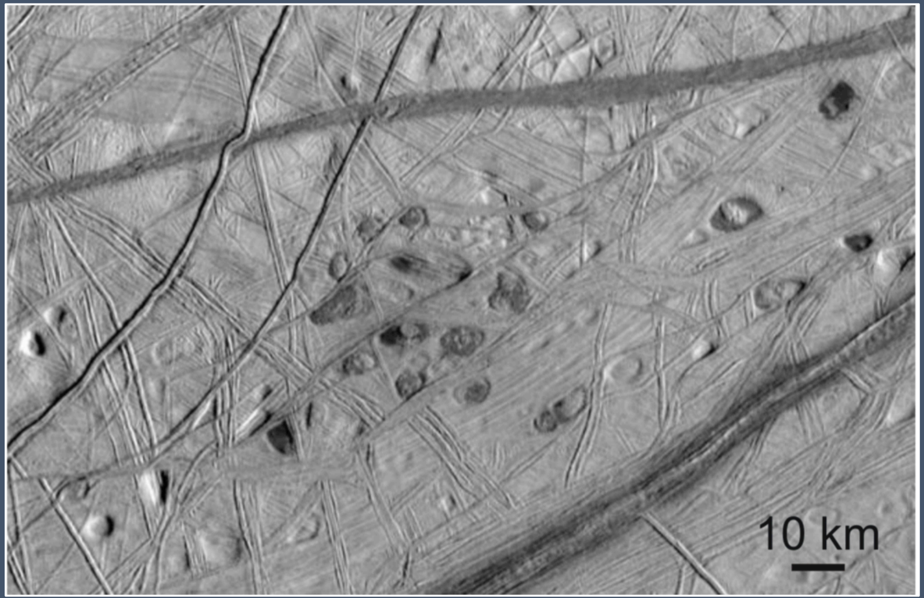
- Fracture
- Tides
- Fluid flow
- Cryovolcanoes
- (Impacts)

Structure

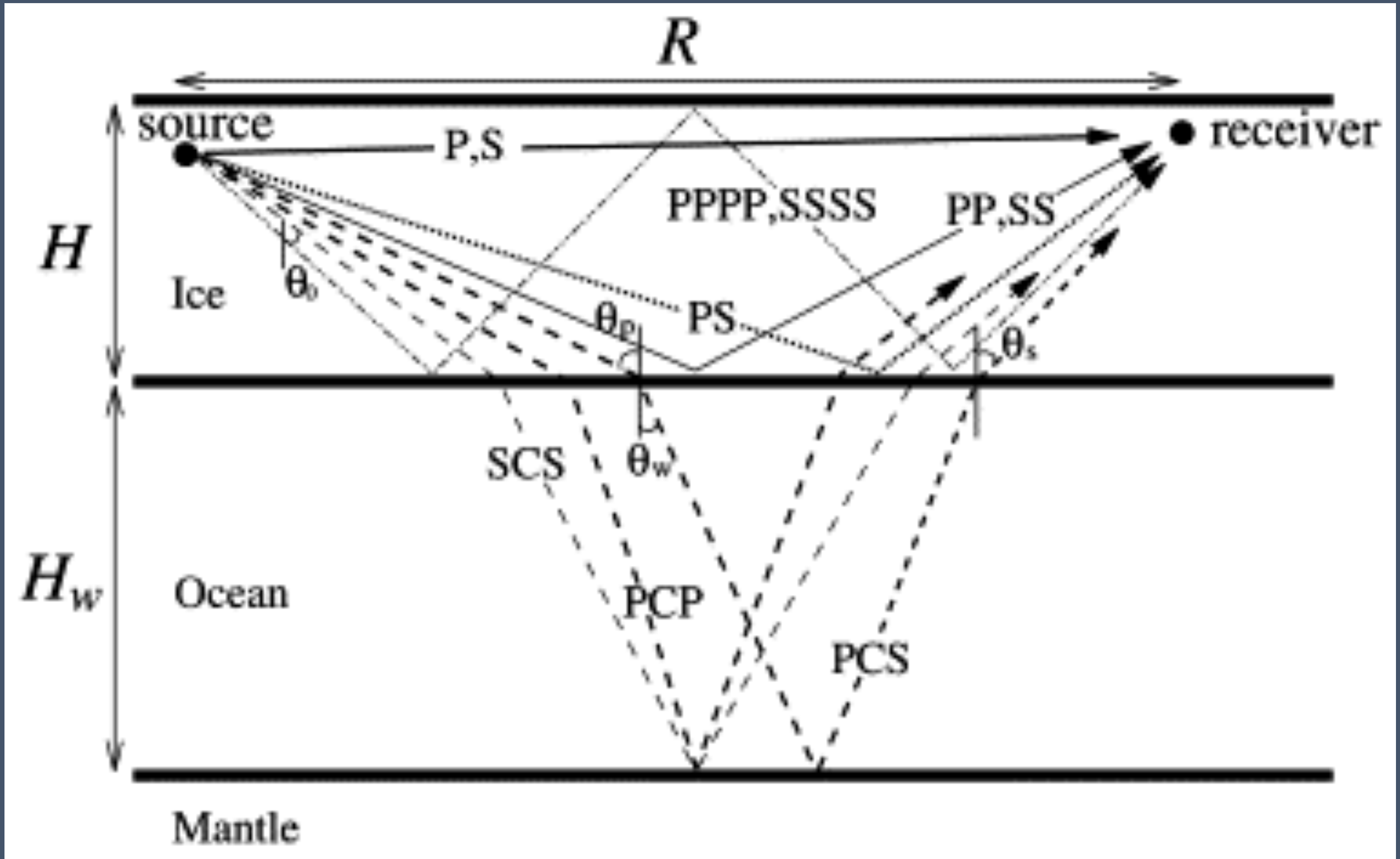
- Ice shell thickness
- Ocean depth
- High pressure ices
- Rocky interior
- Near-surface material







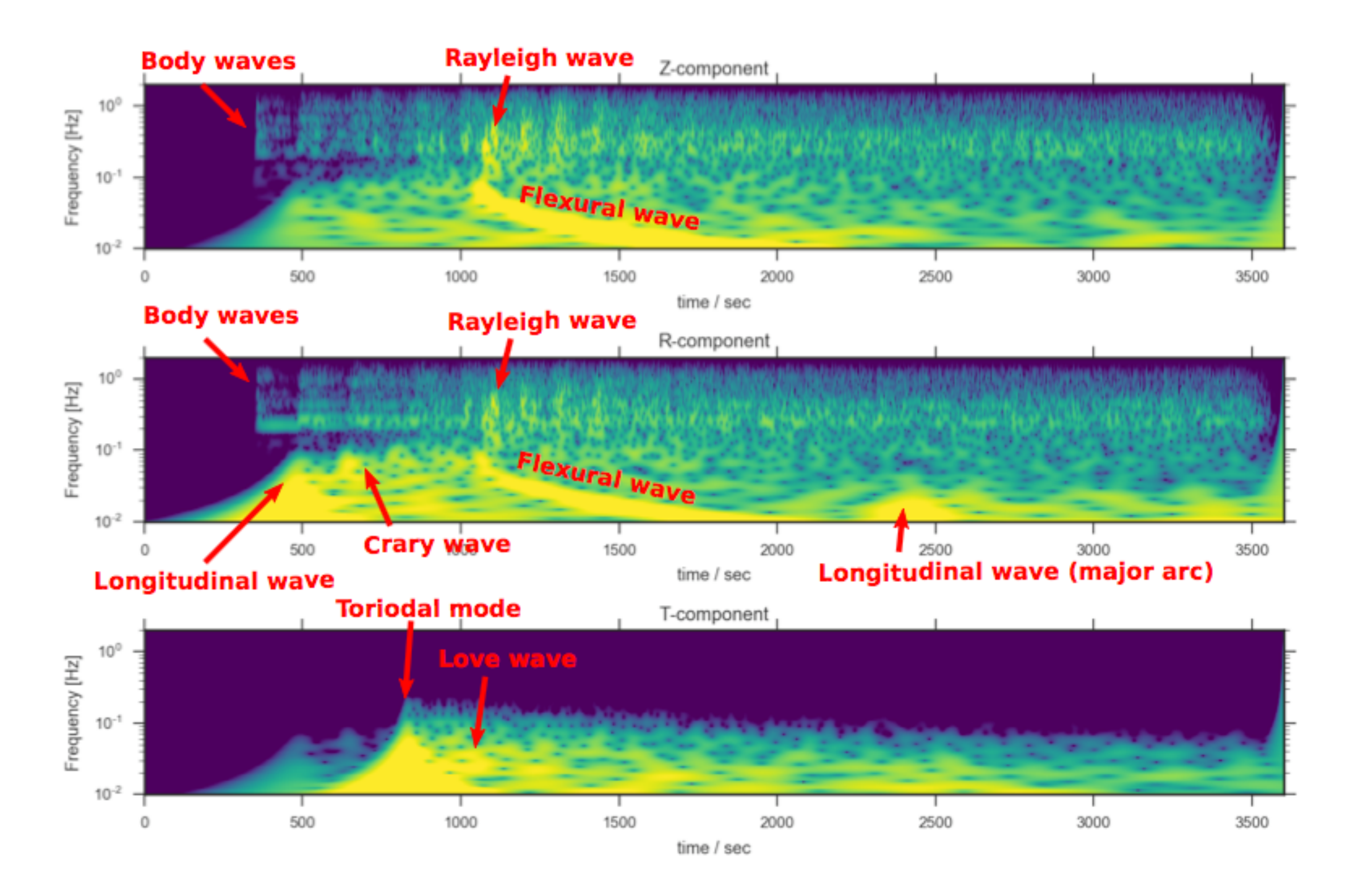
Icy ocean world structure from body waves



From Lee et al., 2003

The most obvious target for seismology is to determine ice shell thickness and ocean depth via timing of reflected waves

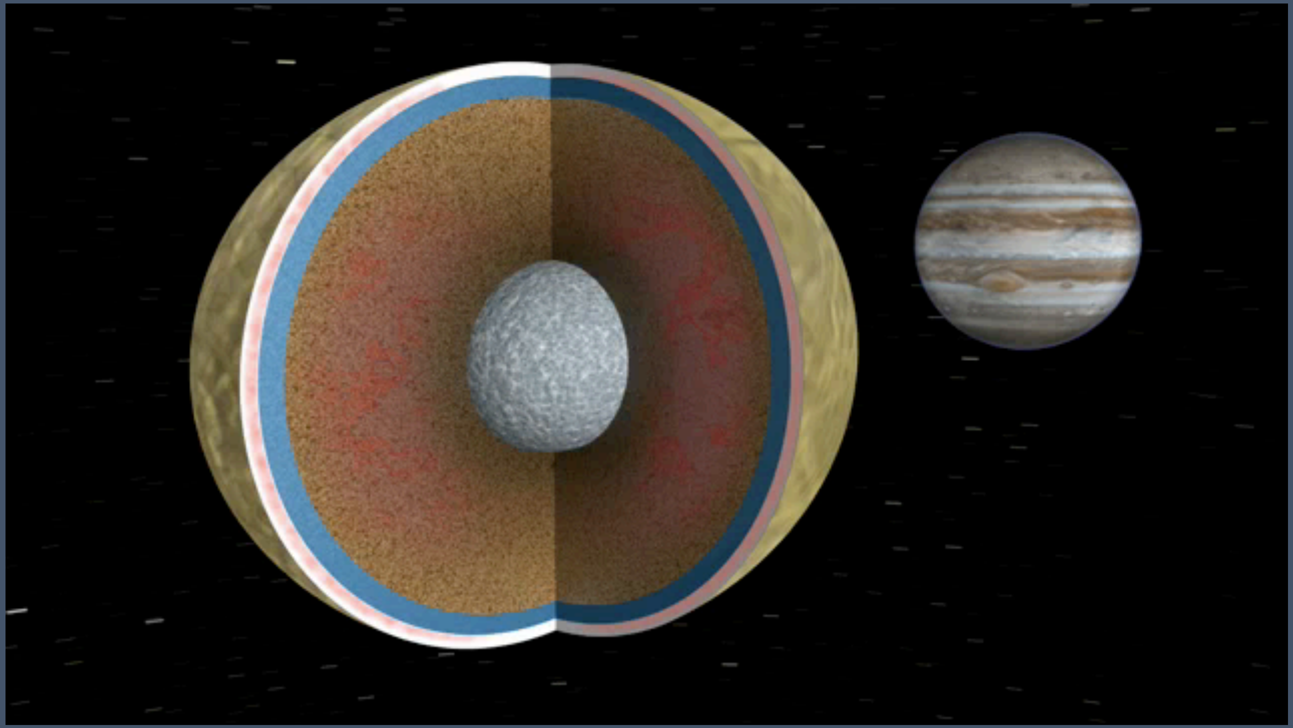
Broadband signals are powerful



Spectrograms from synthetic icy ocean world signals show several diagnostic signals to determine ice shell thickness and ocean depth. Figure from Stähler et al., 2018

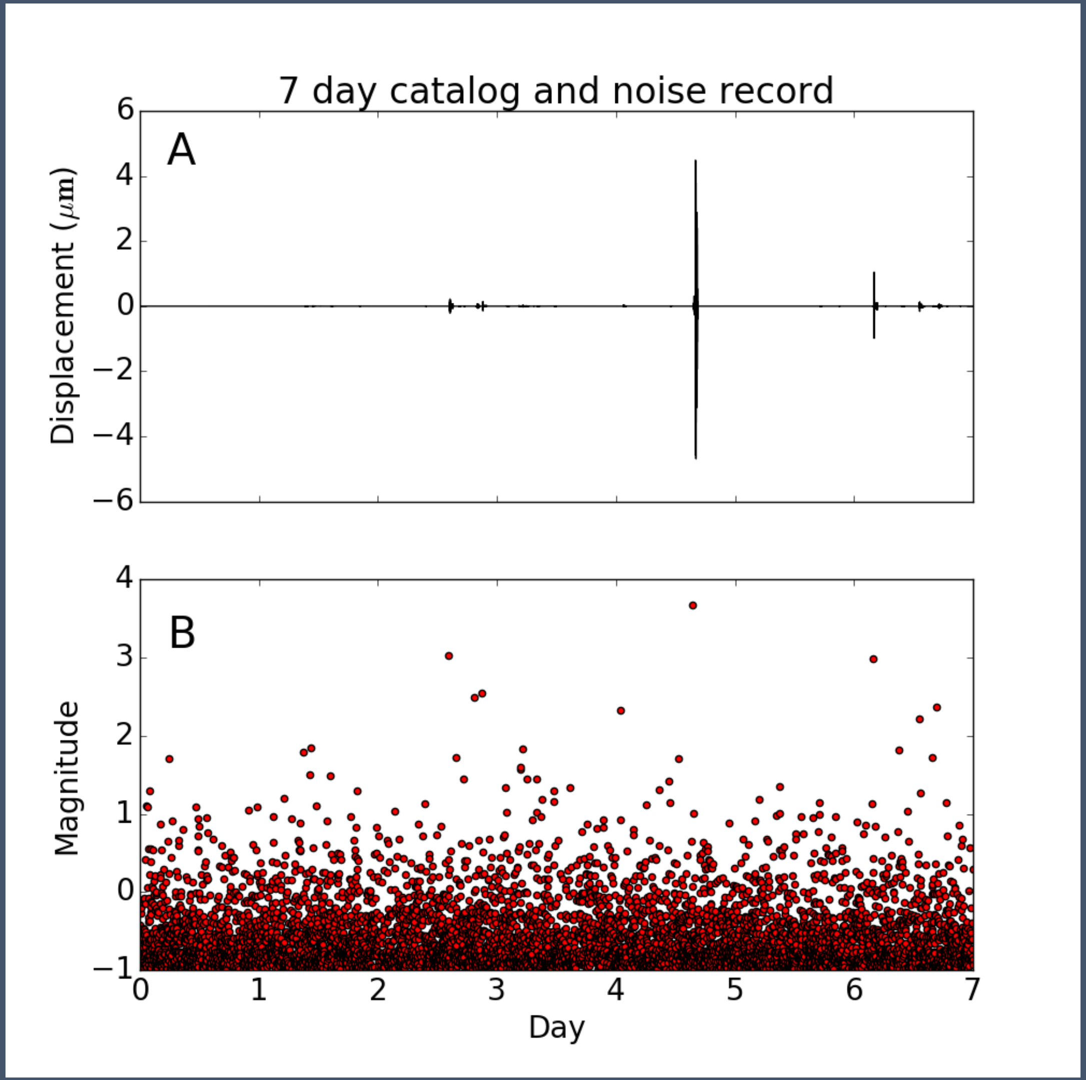
Seismicity and noise sources on icy ocean worlds

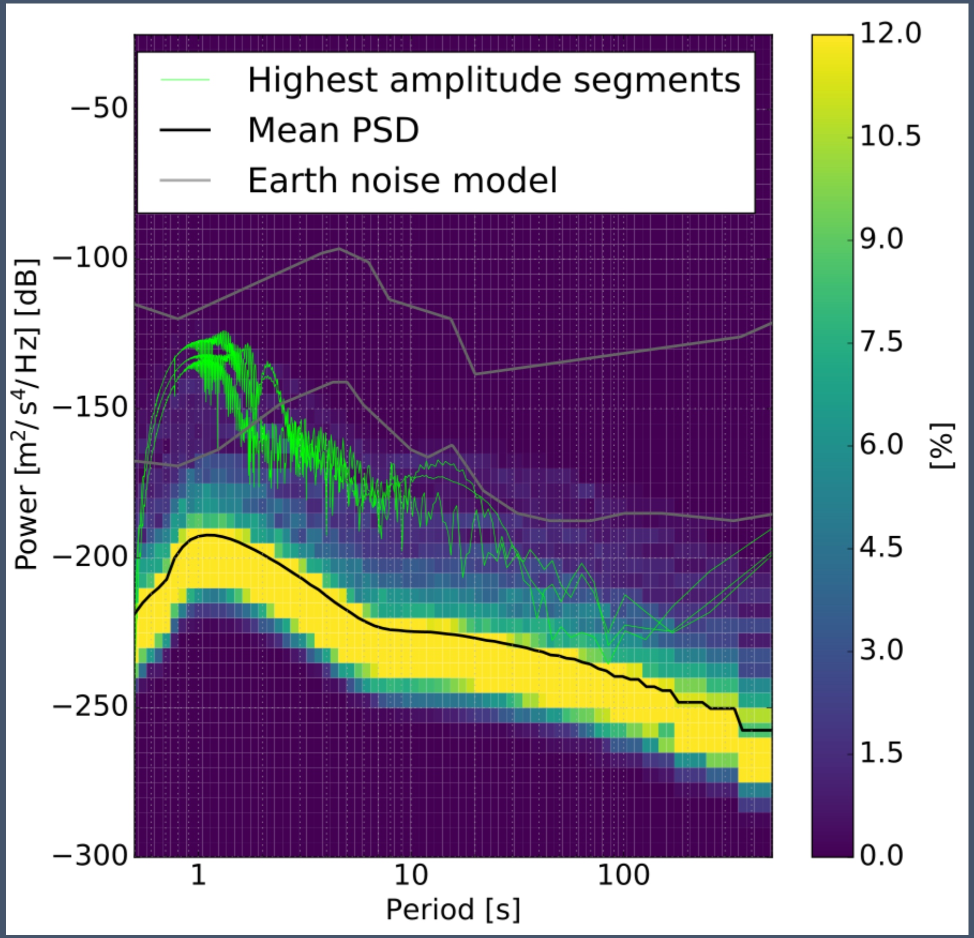
- Tidal cracking (icequakes) – Estimate using tidal dissipation
- Ocean noise – Requires better ocean turbulence modeling
- On Titan, two other noise sources are relevant
  - Waves on ethane/methane lakes – important at high latitudes (?)
  - Atmospheric noise – may be the dominant noise on Titan



Movie credit: JPL/Caltech

Simulated Europa icequake catalogs and noise

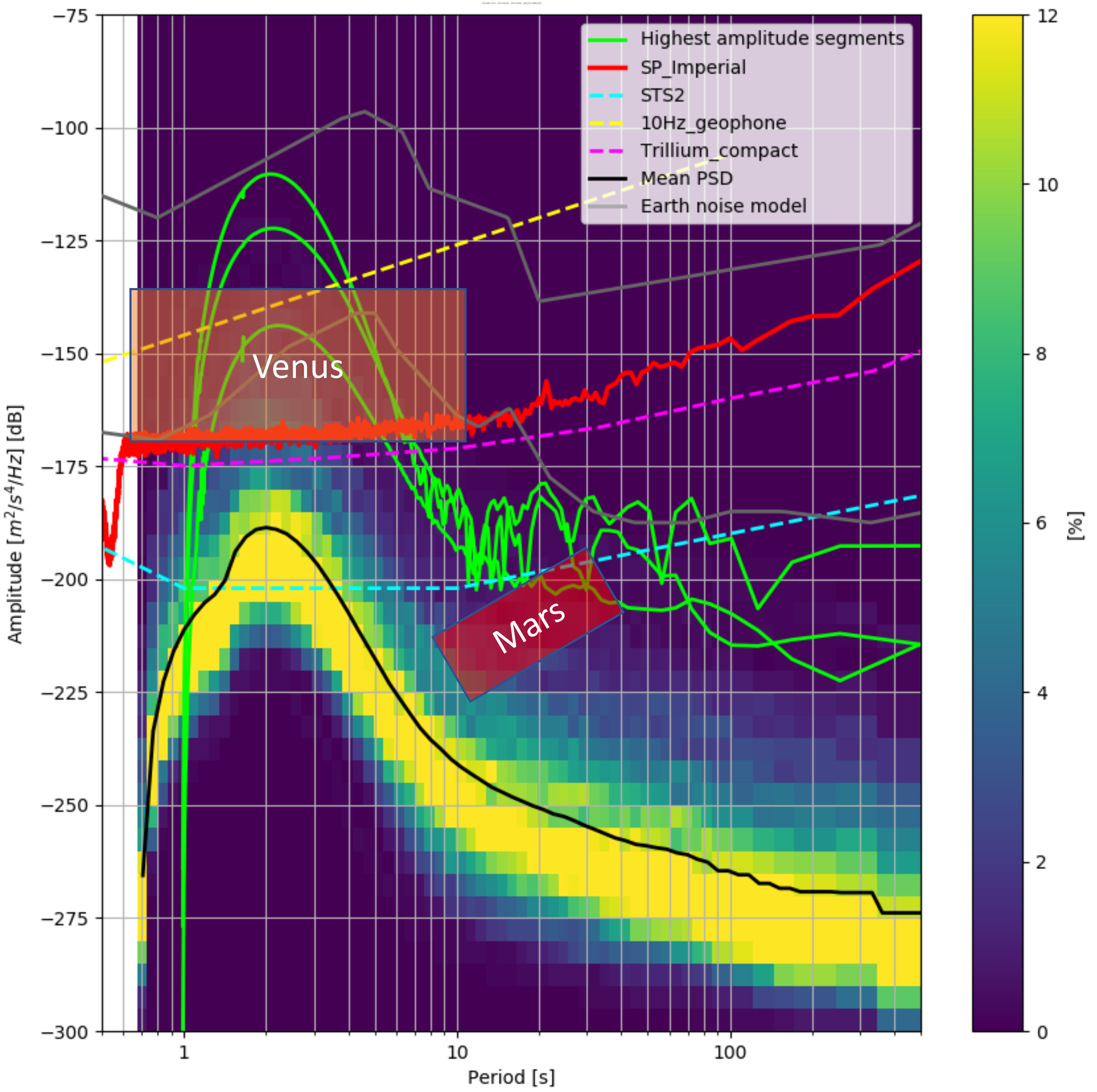




Icequake catalog and synthetic seismic record (left) and estimated acceleration power spectral density for best guess model of Europa seismicity

Atmospheric noise

- For Mars, noise has been simulated with atmospheric circulation models (Murdoch et al., 2017)
- For Venus, background noise may be similar to a quiet Earth station (Lorenz and Panning, 2018)
- Scale between those estimates by the estimated acoustic impedance of the atmosphere at the surface
  - Venus ~ 25 x Titan
  - Titan ~ 220 x Mars



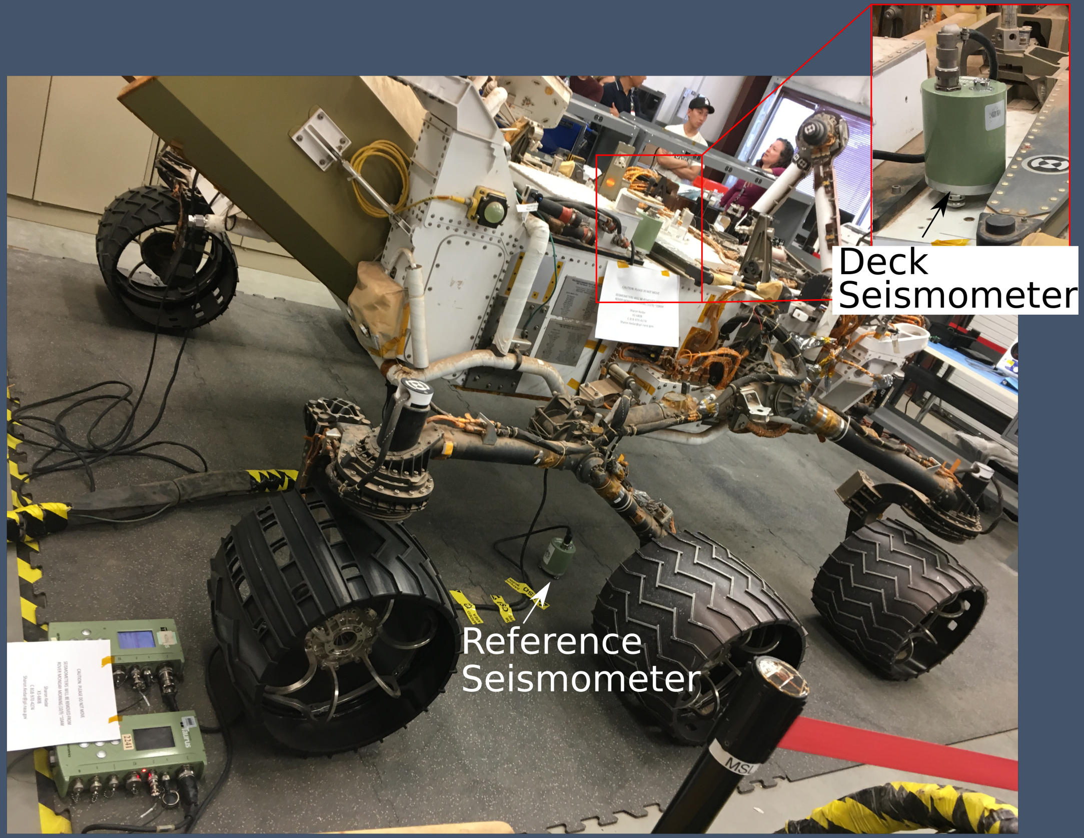
Where do we go from here?

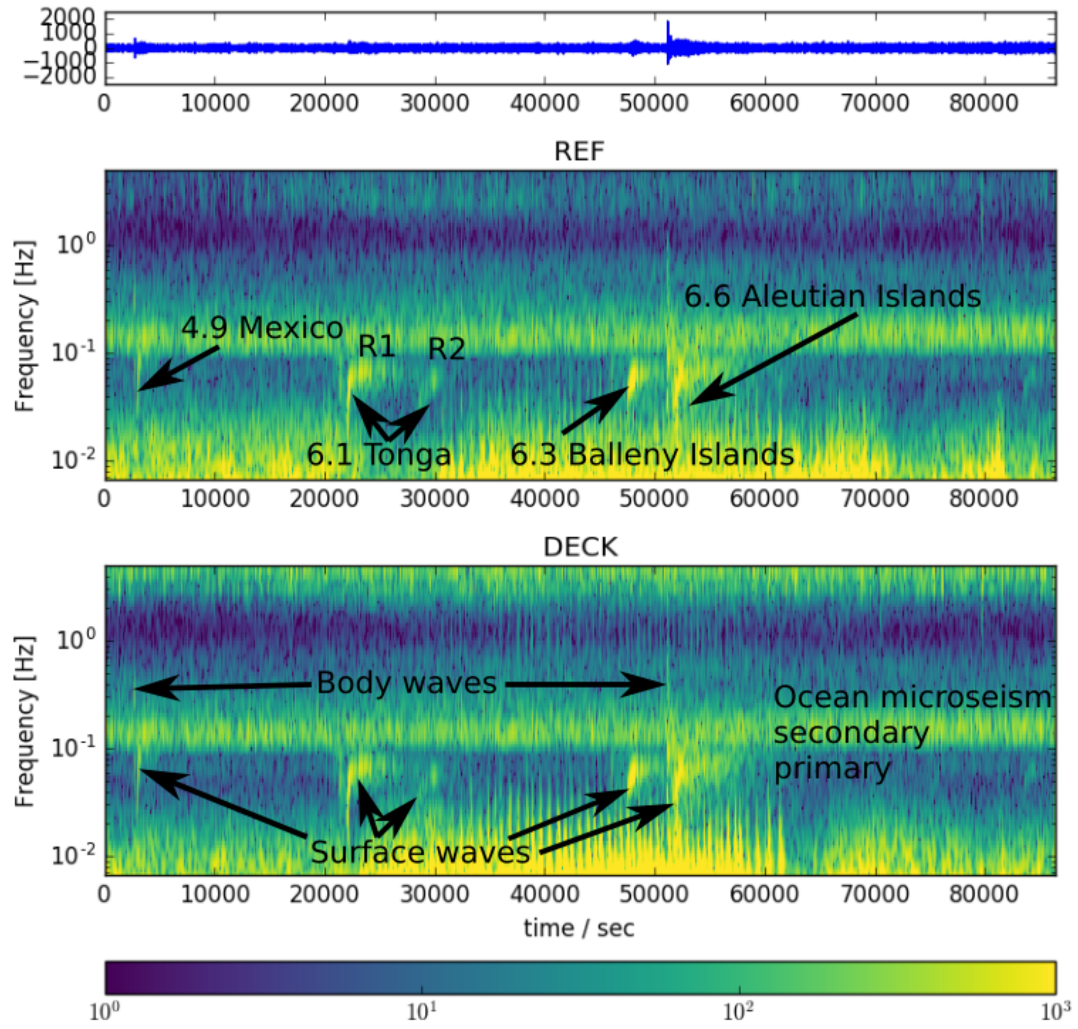
Seismometers on every lander

Investigations for deck deployment

Useful seismic data can be obtained from a simple deck deployment below spacecraft resonant frequencies.

Enables seismology without complex deployment.





Panning and Kedar, 2019

What kind of seismometers?




Earth	Streckeisen STS-2	Trillium Compact	Geophone	MEMS Accelerometer*
Planetary	InSight VBB	InSight SP	Apollo Active Experiment	?*

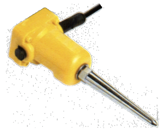
* Technology has not yet reached sensitivity requirements of Earth & planetary science, although the InSight SP is partially MEMS-based

- Very Broad Band (VBB)
- High Dynamic Range
- Ultra sensitive
- $$$$

1.4kg

- Broad Band
- High Dynamic Range
- Sensitive
- $$

~0.1Kg
~3cm



- Narrow Band
- Limited dynamic range
- Strong motions
- $

~0.01Kg
~1cm

- Broad Band
- High dynamic range
- Sensitive
- $

Conclusions

- Planetary seismology is key to detailed interior modeling
- Single station results on Mars can be very powerful
- Seismology on icy ocean worlds looks very different from what we're used to on terrestrial bodies like the Earth (or Mars or the moon)
- There are several signals that can be exploited to learn critical things about icy ocean worlds
- Signals should be large enough on both Europa and Titan to be recorded by a moderately sensitive instrument (InSight SP or Trillium Compact), but not a high-frequency geophone